More Than Stomatal Conductance:

*Modeling **Mesophyll Conductance** to Resolve Global GPP and Water Use Efficiency (WUE) Dynamics*

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Land Model and Biogeochemistry
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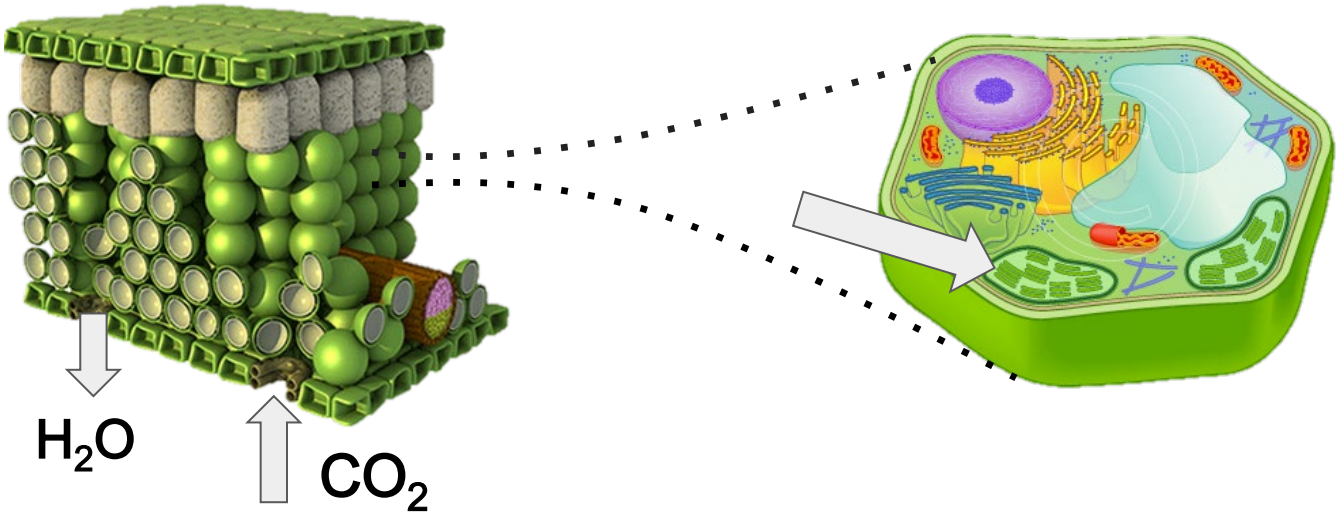
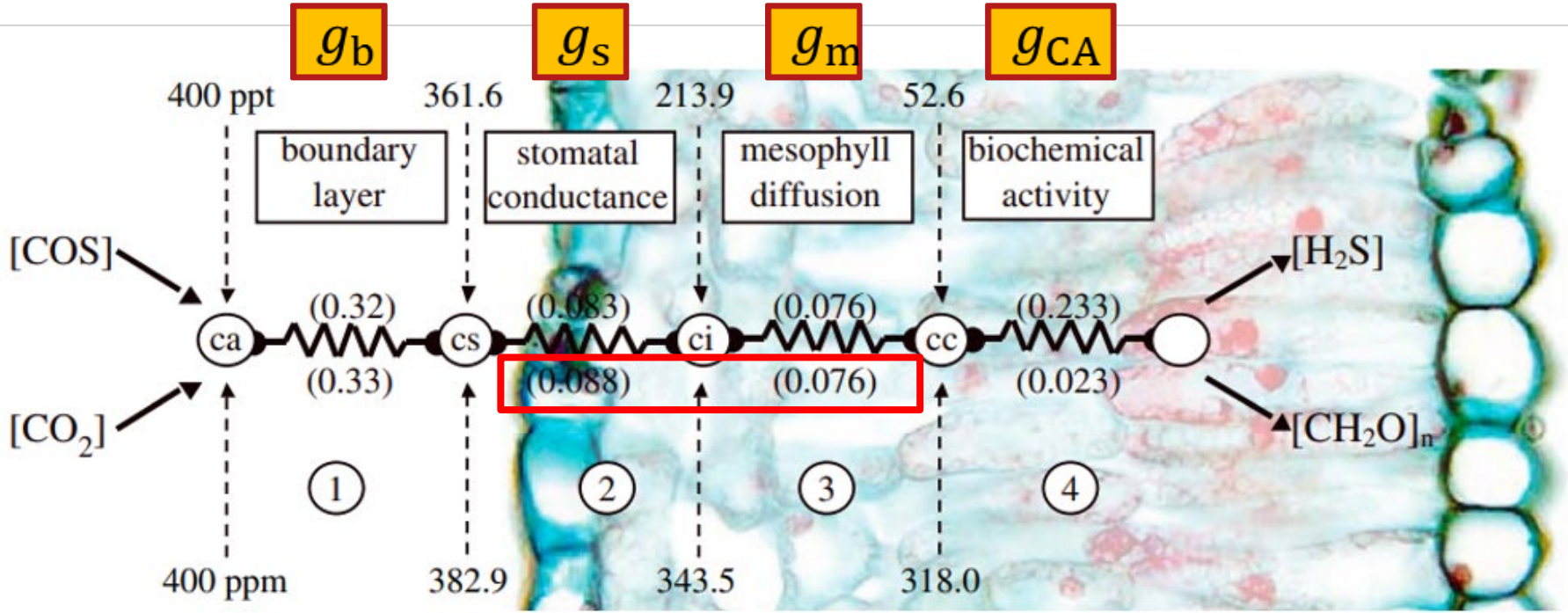
Mesophyll diffusion: A strong barrier for CO_2 availability for photosynthesis



- Stomatal diffusion of CO_2 (gs): Atmosphere to Intercellular air space
- Mesophyll diffusion of CO_2 (gm): Intercellular air space to the interior of chloroplast

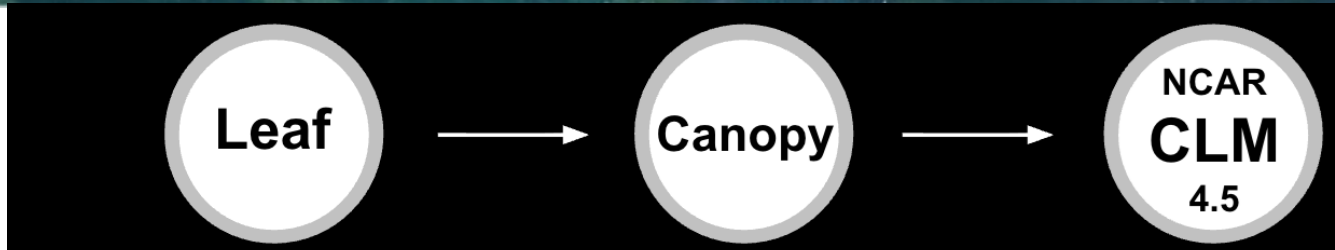
Similar magnitudes of stomatal and mesophyll conductances, but gm long-overlooked in Land Surface Models



The 1st global gm model implemented in CLM4.5

Without explicit consideration of gm, the global CO_2 fertilization effect would be underestimated by 16%

Sun et al., 2014, PNAS



Syntheses of leaf gas exchange measurements

- 130 plant species around the world
- Omission of g_m underestimates chloroplast photosynthetic capacity
- ***Development of an empirical conversion function***

(Sun et al., 2014, PCE)

(Leafweb.ornl.gov)

Syntheses of Literature

- Variation among Plant Functional Types (PFT)
- Variation across vertical canopy gradients
- Variation with environment condition (T, Soil Moisture)

(Gu & Sun et al., 2014, PCE)

Global Implementation

- Structural Update
- Parameter Recalibration
- Numerical Convergence

Consequences on estimated GPP & CO_2 fertilization effect (1901-2010)

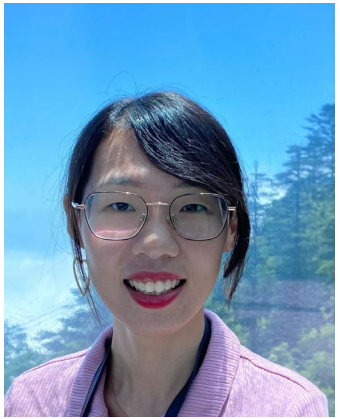
(Sun et al., 2014, PNAS)

(Sun et al., 2012, JGR)

Two Stories with gm in CLM5

1. How much is the global terrestrial photosynthesis (GPP)? *Insights from plant carbonyl sulfide (OCS) uptake - a mechanistic photosynthesis tracer*

2. How do CO2 fertilization and atmospheric dryness (VPD) counteract? *Reconciling the historical trajectory of ecosystem-scale WUE.*



Jiameng Lai
Harvard
Environmental
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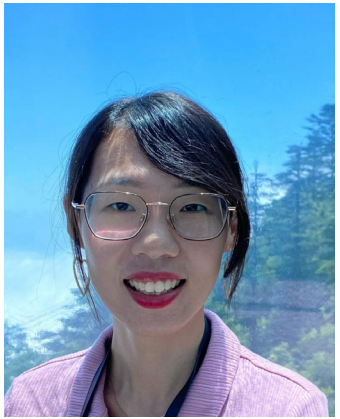

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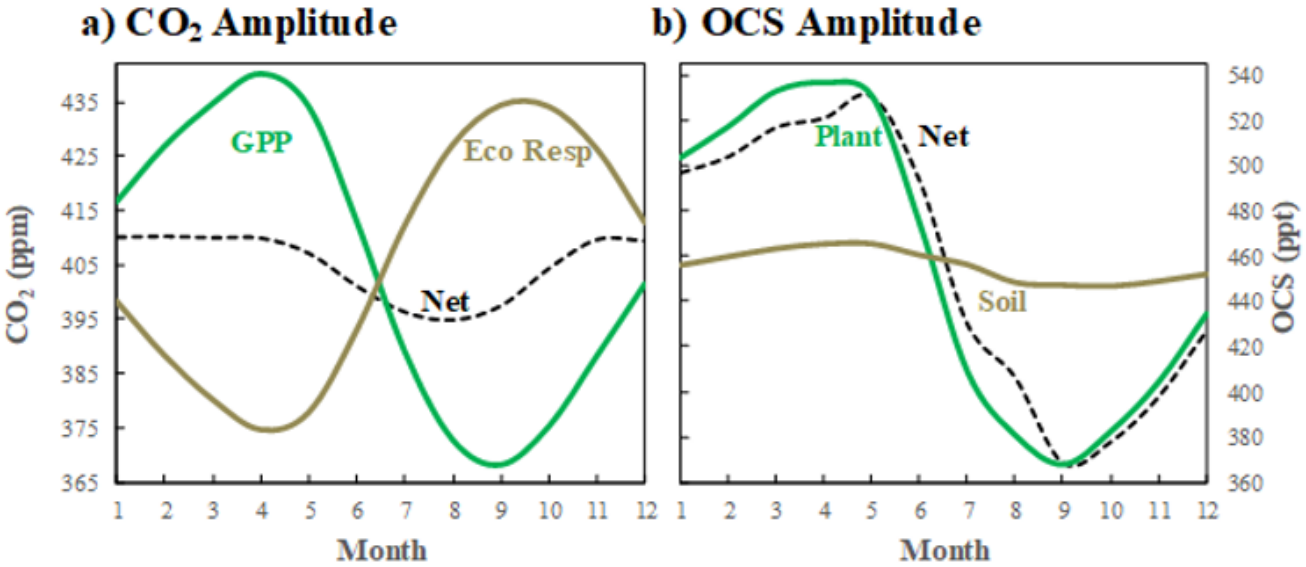
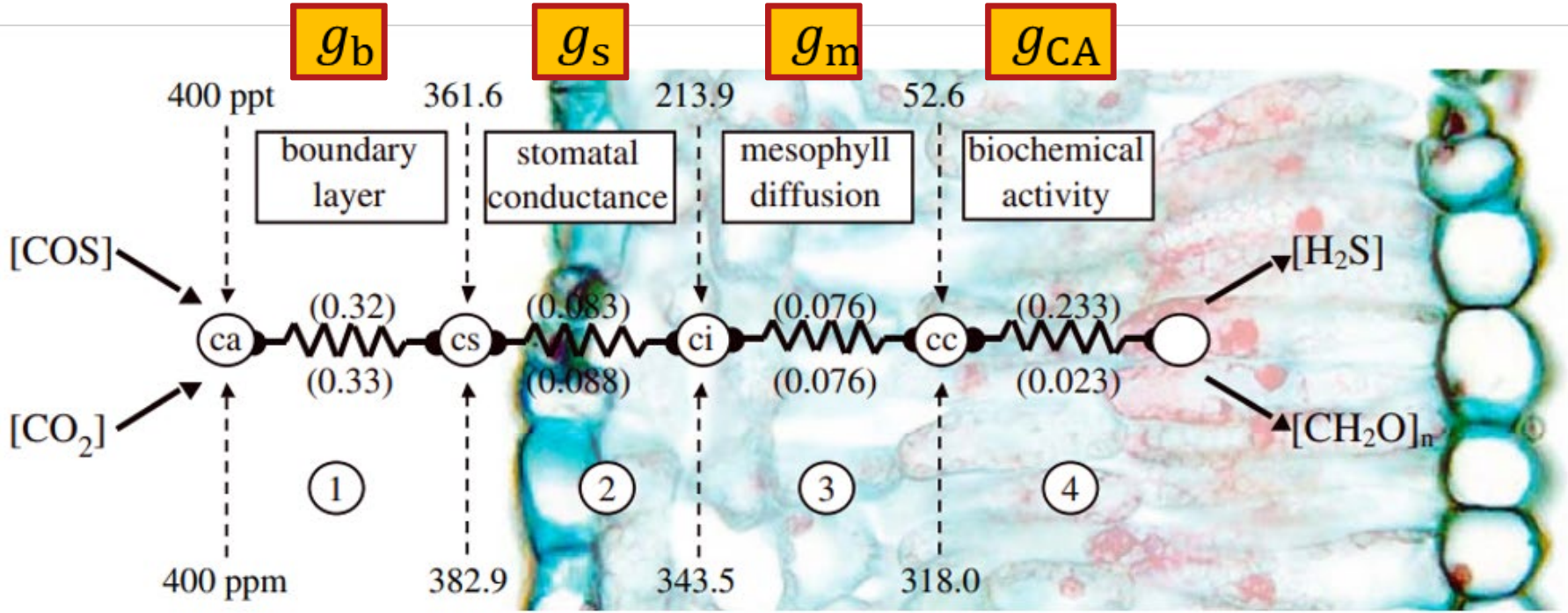
Why OCS - A mechanistic tracer for terrestrial photosynthesis

- OCS seasonal amplitude is mainly driven by the vegetation uptake, which is closely related to GPP



KISS report, 2021

The mechanism: Shared diffusion pathway between OCS and CO_2



Berry et al., 2013, JGR-B

Driving Questions

- How does mesophyll diffusion (gm) impact the magnitude and spatiotemporal dynamics of plant OCS uptake?

- What is the best bottom-up GPP estimate (and its spatiotemporal dynamics) diagnosed with plant OCS fluxes, with explicit consideration of gm?

Technical Workflow

1. Mesophyll conductance (g_m) model

2. OCS model (vegetation and soil)

Sun et al., 2014, PNAS

$$g_m = g_{\max 0} \cdot f_I(x) \cdot f_T(T_l) \cdot f_w(\theta)$$

Berry et al., 2013
Ogée et al., 2016

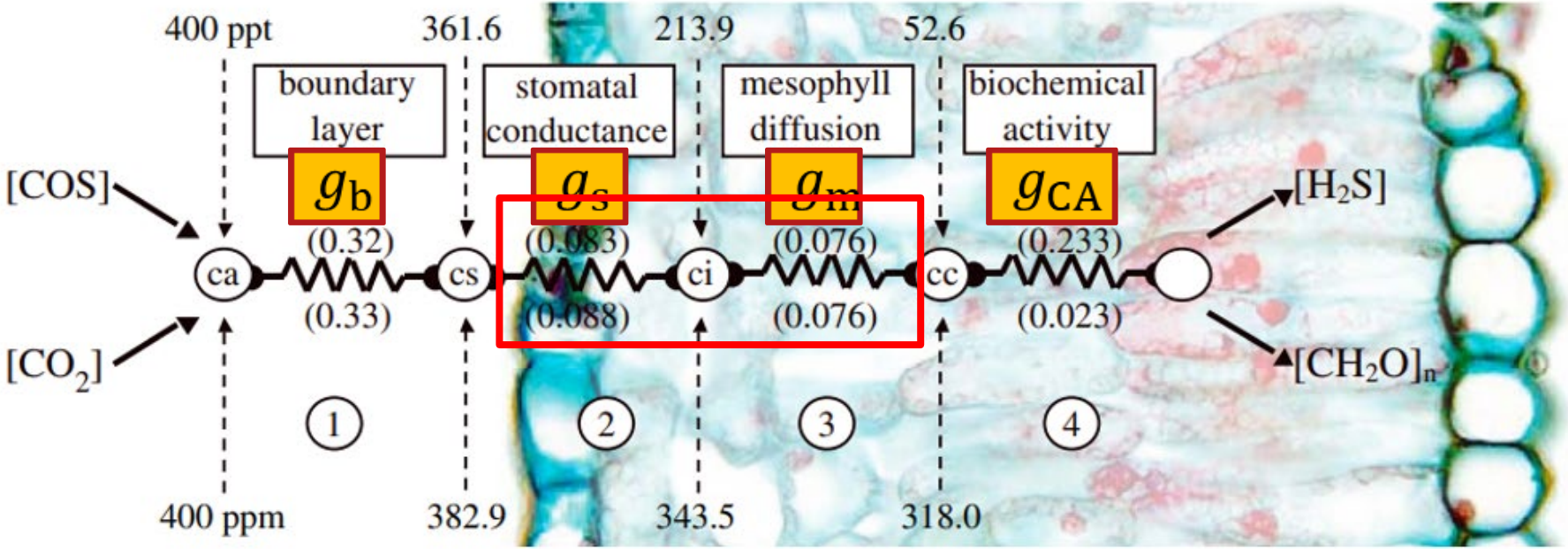
Mesophyll conductance is now dynamically calculated

g_m- explicit: Sun et al. (2014)

$$g_t = (g_b^{-1} + g_s^{-1} + g_m^{-1} + g_{CA}^{-1})^{-1}$$

g_m-implicit: Berry et al. (2013)

$$g_t = (g_b^{-1} + g_s^{-1} + g_{ocs}^{-1})^{-1}$$



Technical Workflow

1. Mesophyll conductance (g_m) model — Sun et al., 2014 PNAS

2. OCS model (vegetation and soil) — Berry et al., 2013; Ogée et al., 2016

LRU (Leaf Relative Uptake)

3. GPP diagnosed from OCS

$$GPP = F_{ocs\_veg} \frac{[CO2]_a}{[OCS]_a} \frac{1}{LRU}$$

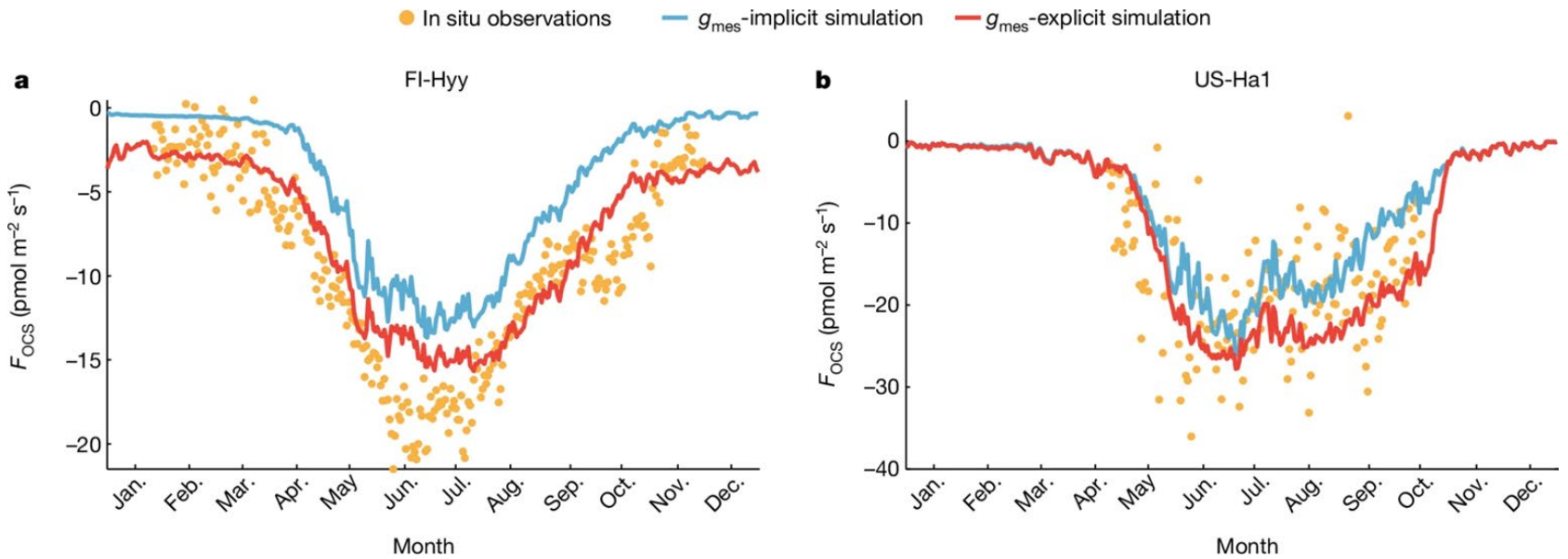
- In-situ obs.

- In-situ obs.,
- FvCB,
- Satellite-based
- Reco,
- O18

Implement to NCAR CLM5

OCS fluxes: gm-explicit outperforms gm-implicit simulations in capturing observed seasonal dynamics

An explicit and mechanistic model representation of gm is necessary to accurately characterize the magnitude and temporal dynamics of ecosystem OCS fluxes.

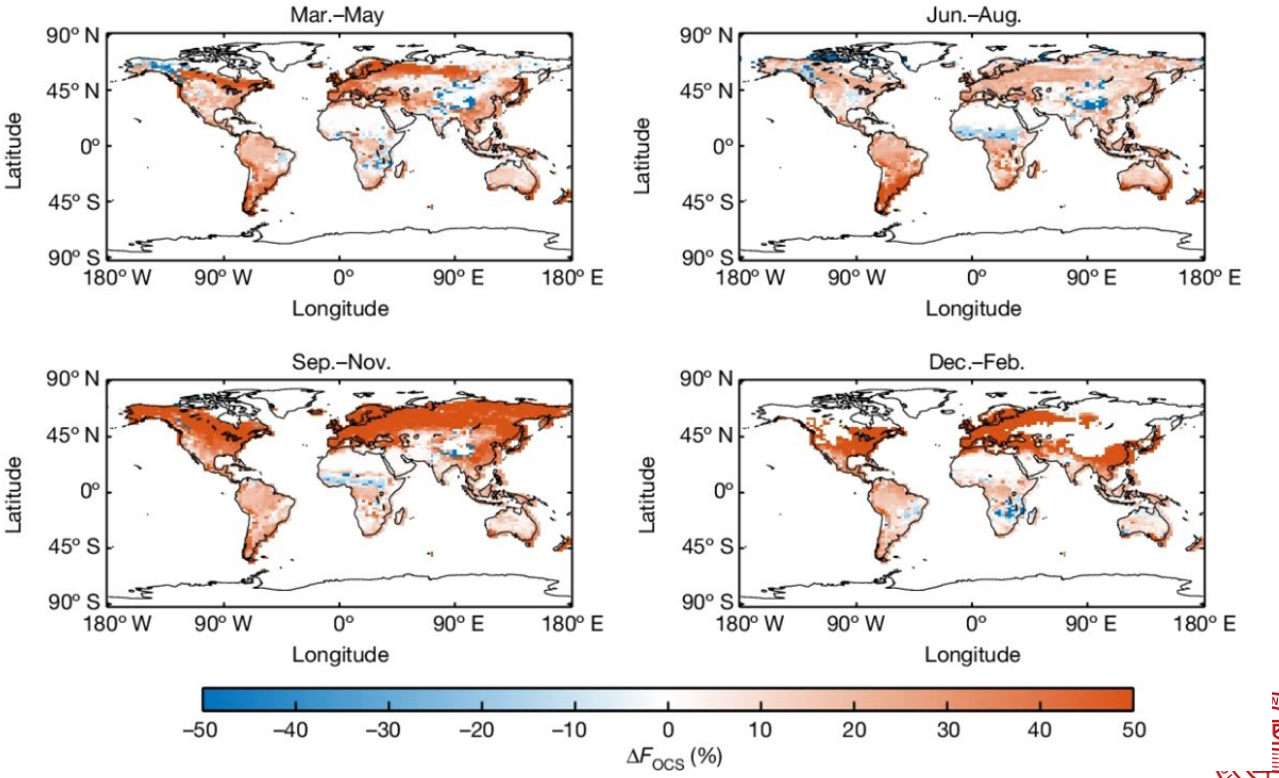


Lai et al., 2024, Nature

Spatially and Temporally varying impacts of gm on OCS fluxes

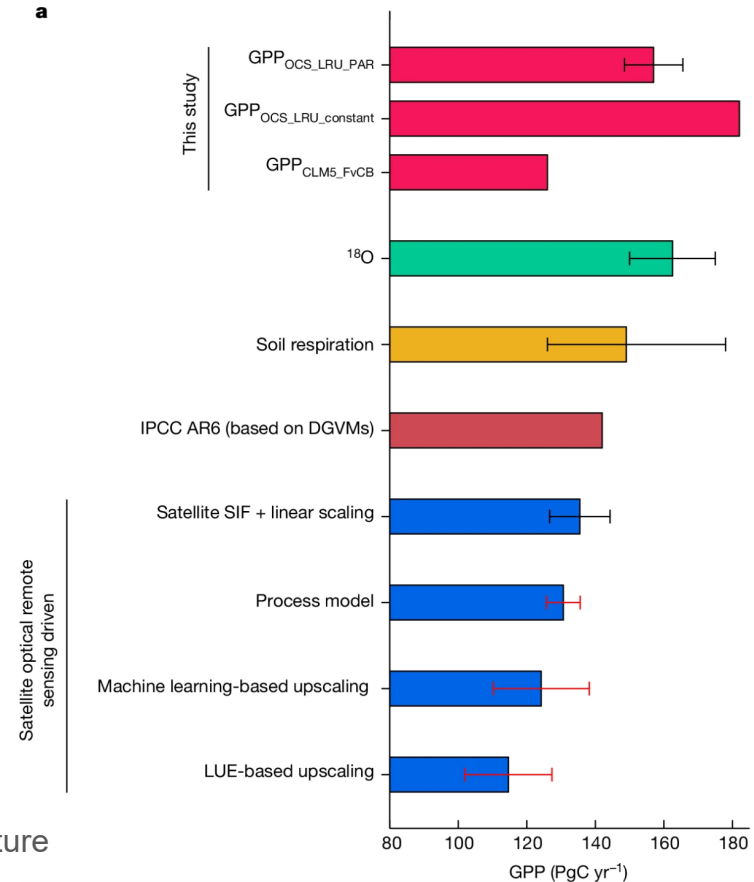
- gm-explicit OCS is larger than that of gm-implicit for almost all biomes, except C3 arctic grasses
- Their differences are seasonally asymmetrical.

ΔFocs = [gm-explicit] - [gm-implicit]



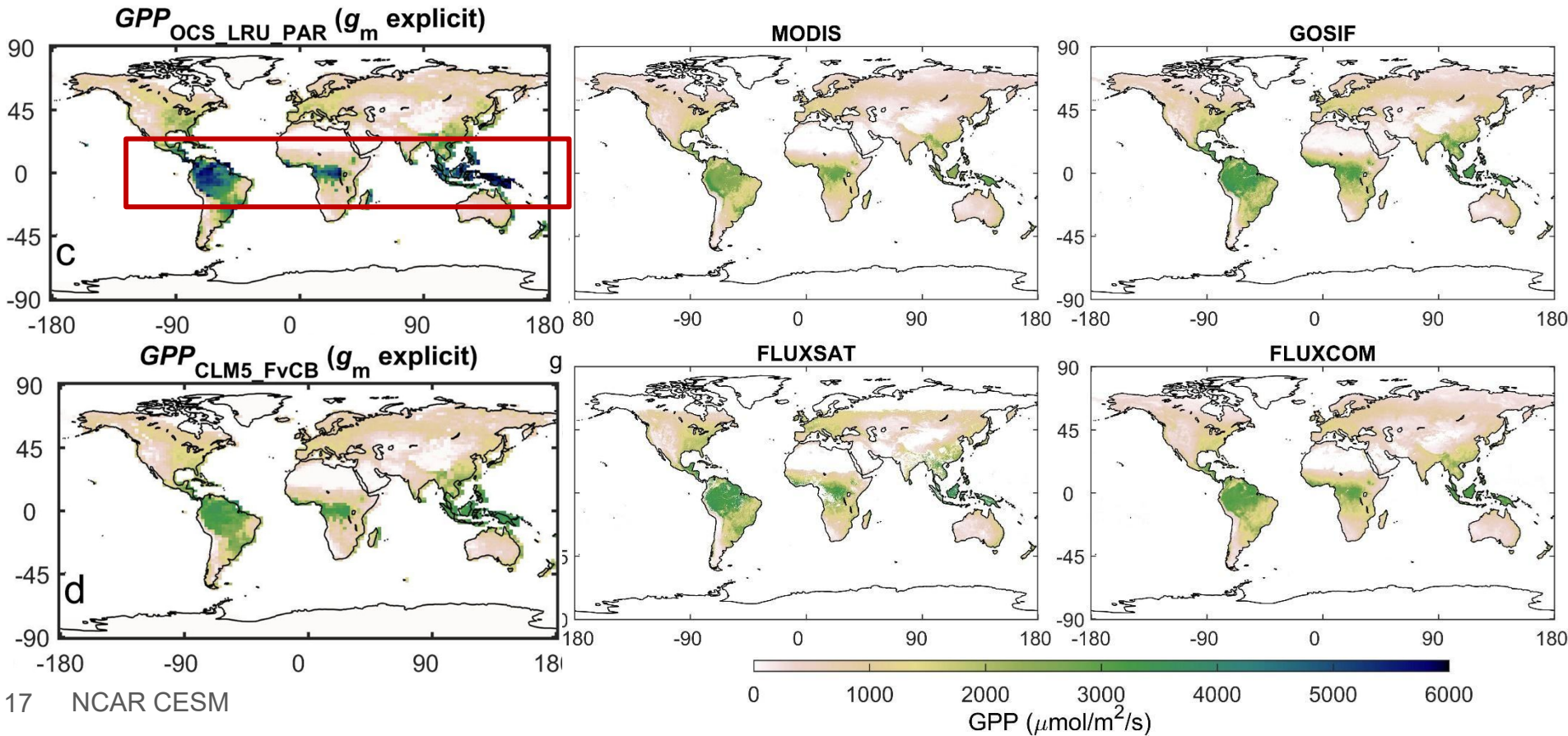
What is the global GPP inferred from OCS?

- **OCS based**: 157 (∓8.5) PgC/yr (2000-2010)
- **Oxygen-isotope**: 150–175 PgCyr-1 (Welp et al., 2011, Nature)
- **Soil respiration**: 149 (-23 ~ +29) (Jian et al., 2020, Nature Comm.)
- **Satellite Optical RS**: 120~125 Pg C/yr
- **Satellite SIF**: ~135 Pg C/yr



Lai et al., 2024, Nature

The spatial distribution of GPP inferred from OCS



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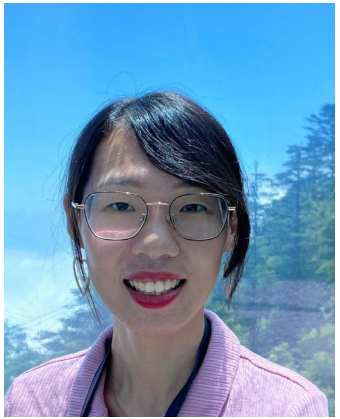

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Inconsistent historical eWUE trajectories by previous studies

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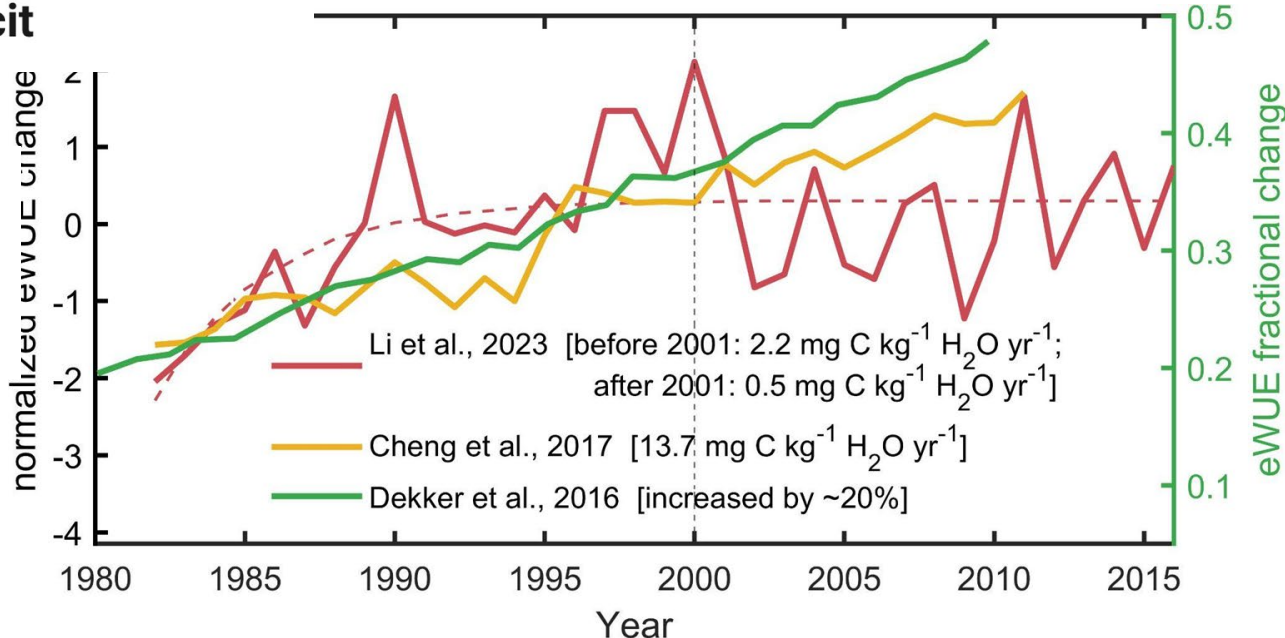
Global water use efficiency saturation due to increased vapor pressure deficit

$$eWUE = \frac{GPP}{ET} = \frac{GPP}{T} \cdot \frac{T}{ET}$$

$$eWUE \approx \frac{GPP}{G_s} \cdot \frac{p_s}{VPD} \cdot \frac{T}{ET} \approx iWUE \cdot \frac{p_s}{VPD} \cdot \frac{T}{ET}$$



Driving Questions

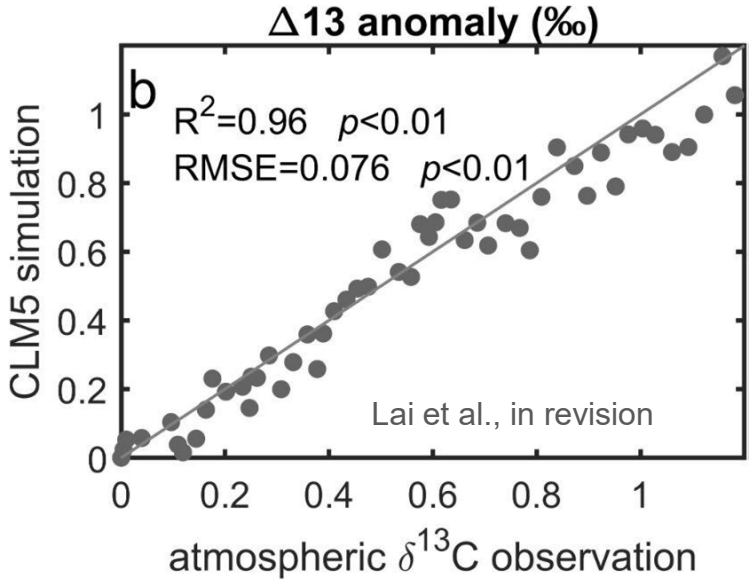
- What is the historical trajectory of eWUE, that is consistent across independent approaches?

- What are the relative roles of VPD and CO2 in shaping the historical pattern of eWUE?

The workflow

$$\Delta = a + (b - a)\,(C_i/C_a) - (b - a_m)\,(A/C_a)/g_i - f\Gamma^*/C_a$$

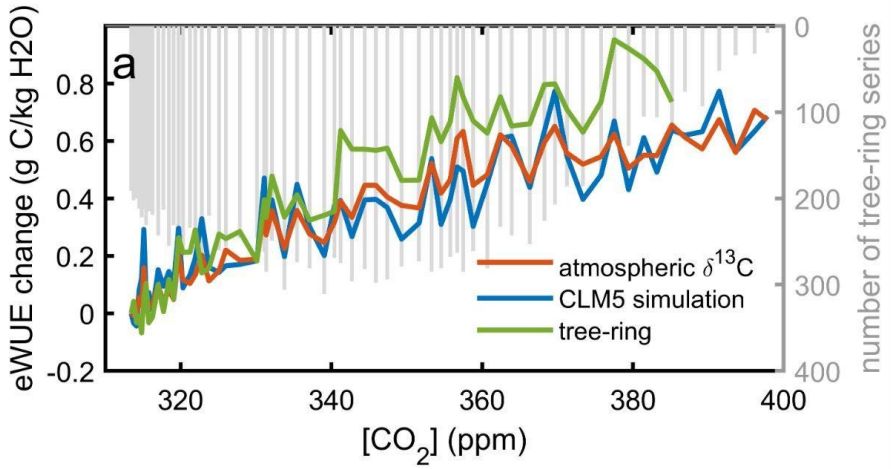
Keeling et al., 2017, PNAS



- Step 1: Inferring global iWUE trend using independent 13C datasets —from atmospheric δ13C observations, tree-ring records, and CLM5 simulations
- Step 2: Inferring global eWUE:

$$eWUE \approx \frac{iWUE}{VPD} \cdot p_s \cdot \frac{T}{ET} \propto \frac{CO_2}{VPD}$$

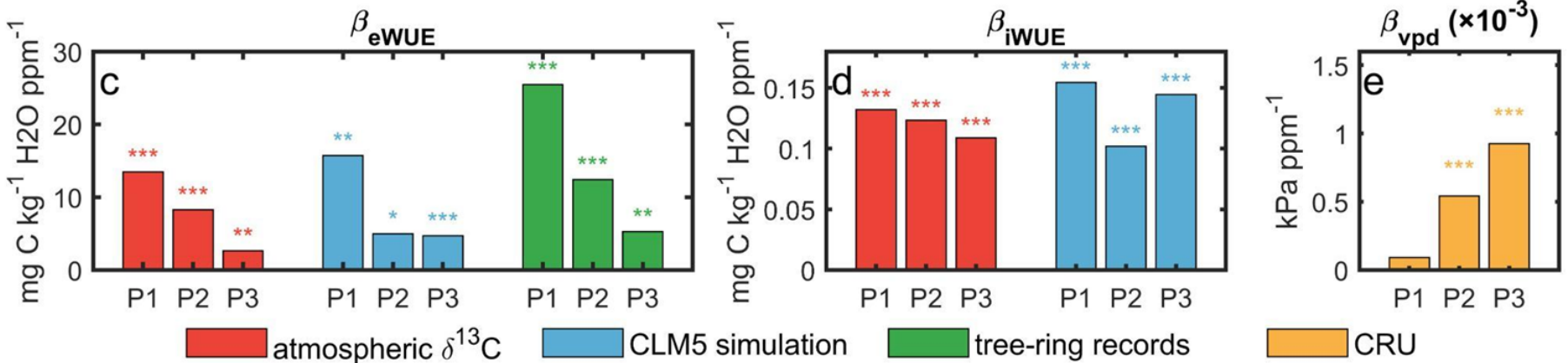
Decelerated but persistent eWUE growth due to the CO2 fertilization effect from 1951 to 2014



- A persistent increase in global eWUE (1951-2014), consistently revealed by atmospheric δ13C observations, tree-ring records, and CLM5 simulations
- A positive β_{eWUE} despite a gradual slowdown over time

Lai et al., in revision

P1: 1951-1970; P2: 1971-1990; P3: 1991-2014



Summary

1. OCS-based global GPP estimate aligns closely with independent estimates derived from ^{18}O and soil respiration, challenges prevailing satellite-derived products.
2. CO_2 Outweighs VPD in Controlling Global Ecosystem Water Use Efficiency

We seek convergence of multiple independent evidences